Predictive Power Control of Doubly-Fed Induction Generator for Wave Energy Converters

Mouna Lagoun, Soumia Nadjem, Atallah Benalia, Mohamed Benbouzid

2012 2nd International Symposium on
Environment-Friendly Energies and Applications (EFEA) Northumbria University

Predictive Power Control of Doubly-Fed Induction Generator for Wave Energy Converters

M.S. Lagoun[1,2], S. Nadjem[1], A. Benalia[1] and M.E.H. Benbouzid[2]
[1]University of Laghouat, LACoSERE, Laghouat, Algeria
[2]University of Brest, EA 4325 LBMS
Rue de Kergoat, CS 93837, 29238 Brest Cedex 03, France
mouna.lagoun@univ-djelfa.dz, a.benalia@mail.lagh-univ.dz and Mohamed.Benbouzid@univ-brest.fr

***Abstract*—Solutions to today energy challenges need to be explored through alternative, renewable and clean energy sources to enable a diverse energy resource plan. An extremely abundant and promising source of energy exists in oceans. There are several wave energy converters to harness this energy. Some of them, as in tidal applications, use the Doubly-fed induction generator (DFIG). This paper deals then with a model-based predictive power control of a DFIG-based Wave Energy Converter (WEC). In the proposed control approach, the predicted output power was calculated using a DFIG linearized state-space model. The DFIG-based WEC power tracking performances further illustrates the dynamic features of the proposed predictive power control approach.**

***Index Terms*—Wave energy converter (WEC), doubly-fed induction generator (DFIG), predictive power control.**

I. INTRODUCTION

The world energy demand is increasing at an alarming rate, and producing electricity from alternative or renewable energy sources is becoming a necessity. Among renewable energy harvesting technologies which are still being investigated through various industrial and academic group, wave energy harvesting technology has already shown to be practical, since oceans cover almost 70% of the earth's surface [1-2].

Numerous techniques for extracting energy from the sea have been suggested, most of which can be included in one of the following categories: wave energy, marine and tidal current energy, ocean thermal energy, energy from salinity gradients (osmosis), and cultivation of marine biomass. The global theoretical energy from waves corresponds to 1500 TWh/year, which is about 100 times the total hydroelectricity generation of the whole planet [3].

To harness the power energy in waves present a different set of technical challenges and a wide variety of designs have been suggested. There are many devices which are generally categorized by the installation location and the power take-off. Therefore, most devices can be characterized as belonging to six types. These are attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping device, and submerged pressure differential [4-5].

In all WECs, a mechanical interface is used to convert the slow rotational speed or reciprocating motion into high speed rotational motion for connection to a conventional rotating electrical generator as a DFIG (Fig. 1).

The control of the active and reactive power is achieved with a rotor current controller.

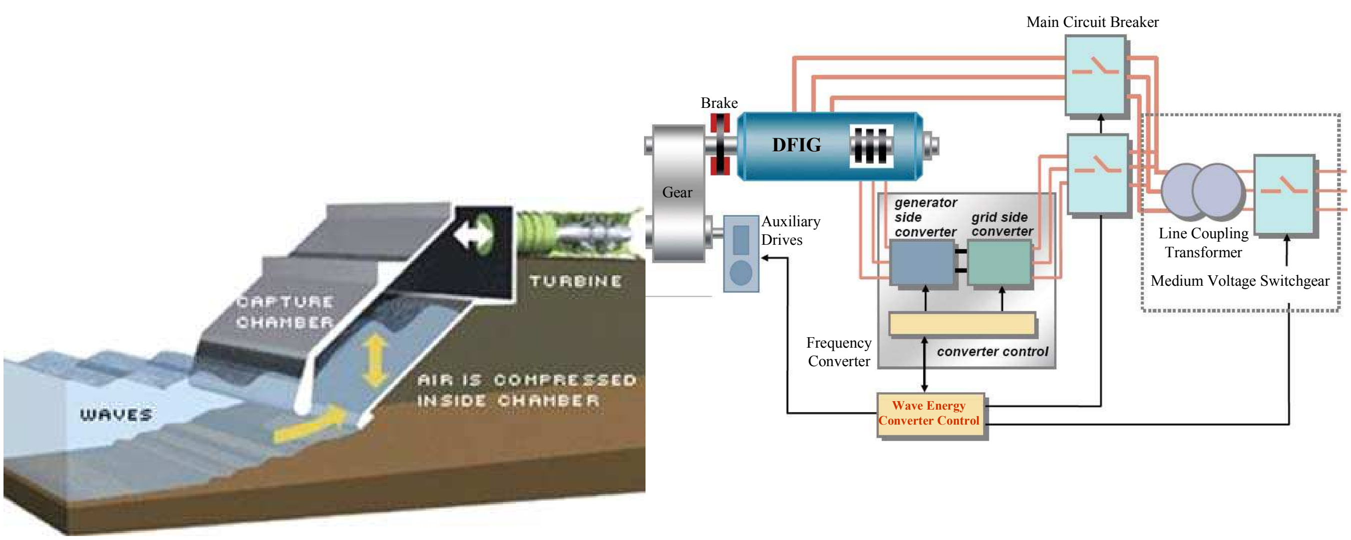


Fig. 1. An illustrative example of DFIG-based WEC.

978-1-4673-2911-8/12/$31.00 ©2012 IEEE

Several investigations have been carried-out for that purpose using cycloconverters and classical PI controllers. However, the problem in the use of PI controllers is gains tuning and DFIG terms cross-coupling in the whole operating range. Interesting methods to solve these problems have been presented in [6–10].

Predictive control is another control technique that was applied in machine drives and inverters [11-14]. This paper proposes then a Model-Based Predictive Control (MBPC) strategy for DFIG-based wave energy converters with the main objective to solve the above-cited control problems.

II. DFIG Model and Rotor Current Control

A. Nomenclature

s, (r)	=	Stator (rotor) index;
d, q	=	Synchronous reference frame index;
V (I)	=	Voltage (Current);
ψ	=	Flux;
R	=	Resistance;
L	=	Inductance;
L_m	=	Magnetizing inductance;
σ	=	Leakage coefficient, $\sigma = 1- L_m^2/L_sL_r$;
ω_s (ω_{mec})	=	Synchronous speed (rotor speed) ($\omega_{sl} = \omega_s - p\omega_{mec}$);
p	=	Pole-pair number;
T_e	=	Sampling period;
k	=	Sampling time.

B. DFIG Modeling

For decoupled control, dynamic modeling is required. The DFIG dynamic model written in a synchronously rotating frame d-q is given by [6-7]

$$\begin{cases} \overrightarrow{V}_{s\,dq} = R_s \overrightarrow{I}_{s\,dq} + \dfrac{d\overrightarrow{\psi}_{s\,dq}}{dt} + j\omega_s \overrightarrow{\psi}_{s\,dq} \\ \overrightarrow{V}_{r\,dq} = R_r \overrightarrow{I}_{r\,dq} + \dfrac{d\overrightarrow{\psi}_{r\,dq}}{dt} + j\left(\omega_s - p\omega_{mec}\right)\overrightarrow{\psi}_{r\,dq} \end{cases} \tag{1}$$

$$\text{where } \begin{cases} \overrightarrow{\psi}_{s\,dq} = L_s \overrightarrow{I}_{s\,dq} + L_m \overrightarrow{I}_{r\,dq} \\ \overrightarrow{\psi}_{r\,dq} = L_m \overrightarrow{I}_{s\,dq} + L_r \overrightarrow{I}_{r\,dq} \end{cases} \tag{2}$$

In this context, the DFIG active and reactive power are given by

$$\begin{cases} P = \dfrac{3}{2}\left(V_{ds}I_{ds} + V_{qs}I_{qs}\right) \\ Q = \dfrac{3}{2}\left(V_{ds}I_{ds} - V_{qs}I_{qs}\right) \end{cases} \tag{3}$$

C. DFIG Control

The DFIG power control aims independent stator active and reactive power control by means of rotor current regulation. Stator flux-oriented control is used and it consists in decoupling the d-q axis ($\psi_{ds} = \psi_s$). In this context, the stator current are given by

$$\begin{cases} I_{ds} = \dfrac{\psi_s}{L_s} - \dfrac{L_m}{L_s} I_{dr} \\ I_{qs} = -\dfrac{L_m}{L_s} I_{dr} \end{cases} \tag{4}$$

Using stator flux-oriented, with $V_{ds} = 0$, leads to the following power expressions

$$\begin{cases} P = -\dfrac{3}{2} V_s \dfrac{L_m}{L_s} I_{rq} \\ Q = \dfrac{3}{2}\left(\dfrac{\psi_s}{L_s} - \dfrac{L_m}{L_s} I_{rq}\right) \end{cases} \tag{5}$$

Rotor currents control using (5), allows then the DFIG power control.

Rotor voltages in (1) can be rearranged using (4) an become

$$\overrightarrow{V}_{r\,dq} = (R_r + j\sigma L_r \omega_{sl})\overrightarrow{I}_{r\,dq} + \sigma L_r \frac{d\overrightarrow{I}_{r\,dq}}{dt} + j\frac{L_m}{L_s}\omega_{sl}\psi_s \tag{6}$$

The above equation can be rewritten in state-space form

$$\begin{cases} \dot{x} = Ax + Bu + Gw \\ y = Cu \end{cases}$$

$$\begin{bmatrix} \dfrac{dI_{rd}}{dt} \\ \dfrac{dI_{rq}}{dt} \end{bmatrix} = \begin{bmatrix} \dfrac{-R_r}{\sigma L_r} & \omega_{sl} \\ -\omega_{sl} & \dfrac{-R_r}{\sigma L_r} \end{bmatrix} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{\sigma L_r} & 0 \\ 0 & \dfrac{1}{\sigma L_r} \end{bmatrix} \begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ \dfrac{-\omega_{sl} L_m}{\sigma L_s L_r}\psi_s \end{bmatrix} \tag{7}$$

where C is the identity matrix.

The discretized form is given as

$$\begin{cases} x(k+1) = A_d x(k) + B_d u(k) + G_d w(k) \\ y(k+1) = C_d u(k) \end{cases} \tag{8}$$

where
$$\begin{cases} A_d = e^{AT_e} \cong I + AT_e \\ B_d = \int_0^{\tau} e^{AT_e} B\, d\tau \cong BT_e \\ G_d = \int_0^{\tau} e^{AT_e} G\, d\tau \cong GT_e \\ C_d = C \end{cases} \tag{9}$$

Equation (7) can be discretized considering that the rotor voltage is constant during a control period of the PWM voltage source inverter. It can therefore be written as [11]

$$\begin{bmatrix} I_{rd}(k+1) \\ I_{rq}(k+1) \end{bmatrix} = \begin{bmatrix} 1-\dfrac{R_r T_e}{\sigma L_r} & \omega_{sl} T_e \\ -\omega_{sl} T_e & 1-\dfrac{R_r T_e}{\sigma L_r} \end{bmatrix} \begin{bmatrix} I_{rd}(k) \\ I_{rq}(k) \end{bmatrix} + \begin{bmatrix} \dfrac{T_e}{\sigma L_r} & 0 \\ 0 & \dfrac{T_e}{\sigma L_r} \end{bmatrix} \begin{bmatrix} V_{rd}(k) \\ V_{rq}(k) \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ \dfrac{-\omega_{sl} L_m T_e}{\sigma L_s L_r} \psi_s(k) \end{bmatrix} \tag{10}$$

This DFIG linear discrete space-state model will thereafter be used to calculate the output power in the predictive control context.

III. Model-Based Predictive Control

A. Nomenclature

N_p = Prediction horizon output;
N_u = Control horizon;
Y = Predicted output;
U = Input.

B. MBPC

Model-based predictive control involves a class of control techniques that consists of two main elements: the model of the system being controlled and the optimizer that determines the optimal future control actions. The system model is used to predict the future behavior of the system with control law obtained by optimizing a cost-function [11-12]. The cost-function considers the effort needed to control the deviation between the expected and the real values.

$$Y = Nx(k) + HU + DW_e \tag{11}$$

where

$$\begin{cases} Y = [\,y(k+1) \quad y(k+2) \quad \ldots\, y(k+n_y)\,]^T \\ U = [\,u(k+1) \quad u(k+2) \quad \ldots\, u(k+n_y)\,]^T \\ W_e = [\,w_e(k) \quad w_e(k+1) \qquad w_e(k+N_u-1)\,]^T \\ N = [\,C_D A_D \quad C_D A_D^2 \qquad C_D A_D^{N_p}\,]^T \\ H = \begin{bmatrix} C_D B_D & & & \\ C_D A_D B_D & C_D B_D & & \\ C_D A_D^2 B_D & C_D A_D B_D & C_D B_D & \\ \vdots & \vdots & \vdots & \vdots \\ C_D A_D^{N_p-1} B_D & C_D A_D^{N_p-2} B_D & \cdots & C_D A_D^{N_p-N_u} B_D \end{bmatrix} \\ D = \begin{bmatrix} C_D G_D & & & \\ C_D A_D G_D & C_D G_D & & \\ C_D A_D^2 G_D & & C_D G_D & \\ \vdots & \vdots & \vdots & \vdots \\ C_D A_D^{N_p-1} G_D & C_D A_D^{N_p-2} G_D & \cdots & C_D A_D^{N_p-N_u} G_D \end{bmatrix} \end{cases} \tag{12}$$

N_p choice is critical for the control performance.

The control law is obtained by minimizing the following quadratic cost-function [12-13]

$$J = (Y_{ref} - Y)^T W_y (Y_{ref} - Y) + U^T W_u U \tag{13}$$

If N_u = 1, the entries magnitude represents an average value that allows the outputs to follow the references. Moreover, if N_u > 1, the output will closely track the reference. However, big values will increase the computational costs. The minimal value of J is obtained when

$$\frac{\partial J}{\partial U} = 0$$

For each control cycle, matrices N, D, and H must be updated. The substitution of Y from (11) into (13), allows determining an analytical solution of U.

$$U = (H^T\, W_y\, H + W_u\,)^{-1}\, H^T\, W_y\, (Y_{ref} - Nx(k) - DW_e) \tag{14}$$

The above proposed sensorless MBPC control strategy is illustrated by the block diagram in Fig. 2.

IV. Wave Model for the Extracted Reference Power

Wave motion and wave energy absorption are composed of time-varying oscillatory phenomena. For the study of regular waves, it is necessary to take into account wave climate spectrum that indicates the amount of wave energy at different wave frequencies. Then, the regular wave is modeled and is typically described in terms of power per meter of wave front (wave crest length) [5]

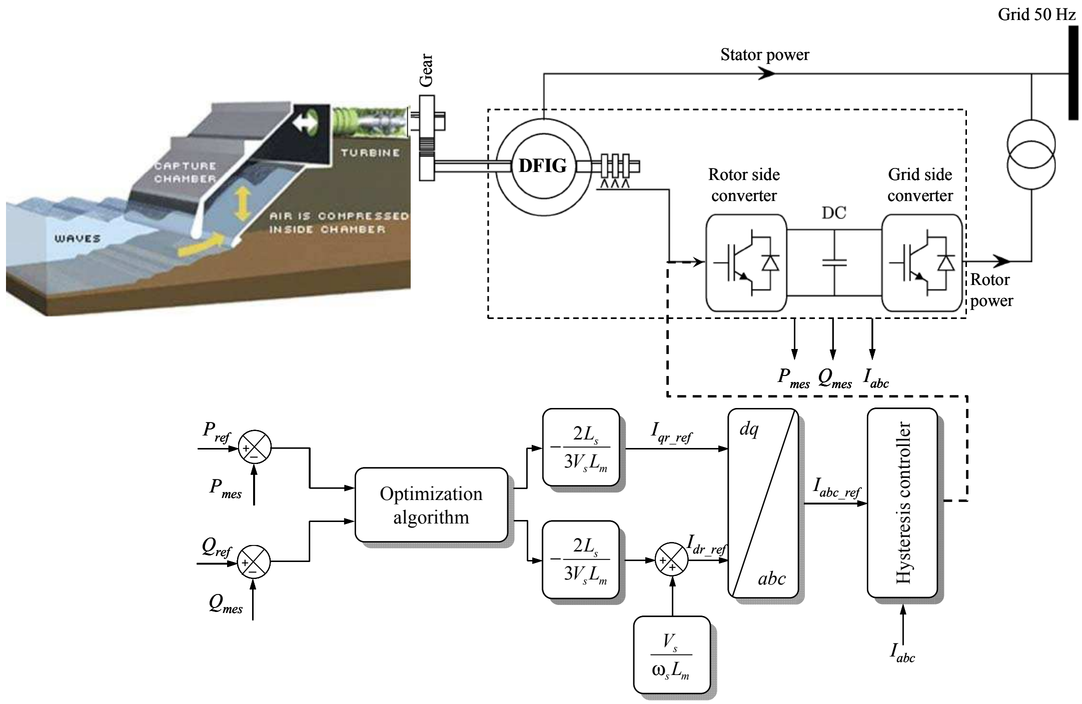


Fig. 2. The proposed DFIG predictive power control strategy.

$$P_{wf} = \frac{1}{8\pi}\rho g^2 A^2 T \tag{15}$$

where ρ is the water density, g is the gravity acceleration, A is the wave amplitude, and T the wave period.

For the proposed control strategy illustration, it has been chosen five successive regular waves, which are different in amplitude and period (Fig. 3). This wave model allows defining the extracted reference power.

V. Simulation Results

The proposed MBPC strategy has been tested for validation using the DFIG whore ratings are given in the Appendix [11].

The weight matrices W_u and W_y elements should be carefully adjusted.

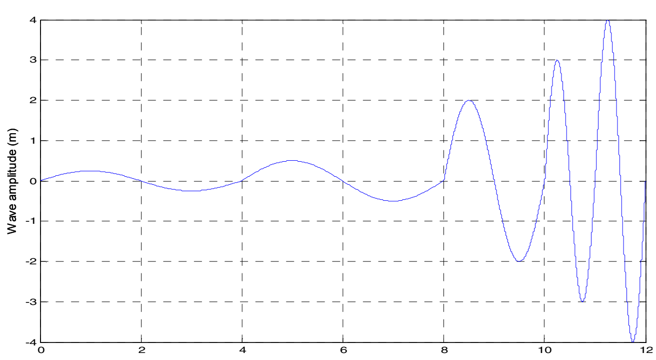


Fig. 3. Wave model for the extracted reference power.

W_u matrix is related the control effort and its elements must be nonzero because they could cause high overshoots. W_y matrix emphasizes each individual prediction of the output that would improve the system time response. According to the above considerations, the following matrices are chosen

$$W_y = \begin{bmatrix} 15 & 0 \\ 0 & 45 \end{bmatrix} \text{ and } W_u = \begin{bmatrix} 0.002 & 0 \\ 0 & 0.01 \end{bmatrix}$$

Moreover, the adopted sampling time T_e = 0.0131 sec.

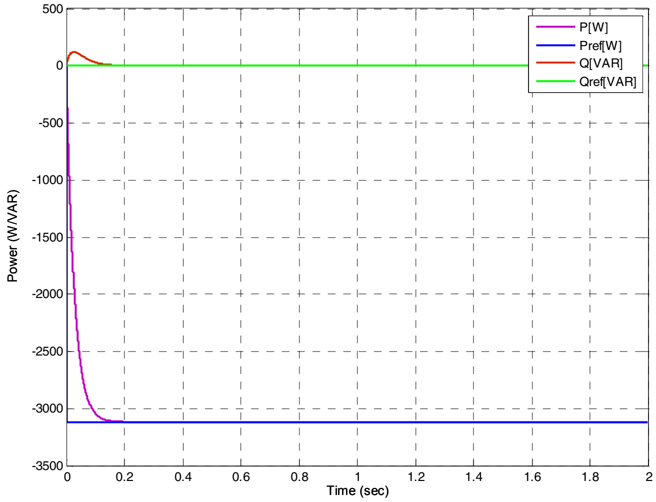
A. Dynamic Response Tests

Initial simulations are carried-out to test the proposed MBPC strategy dynamic response performances. For that purpose, a simple power reference is considered: P = – 3120 W and Q = 0 VAR. The achieved performances, with N_u = 1, are illustrated by Fig. 4. According to Fig. 4a illustrating the dynamic response of both active and reactive powers, it could be easily concluded that the proposed control strategy achieves satisfactory dynamic performances.

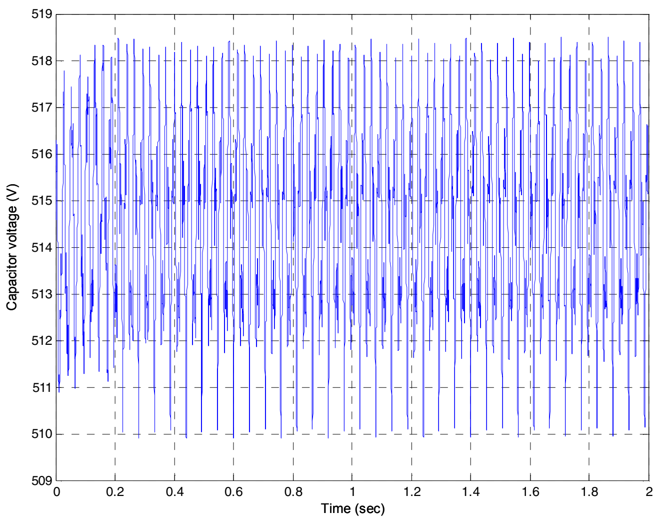
B. Tests using the Wave Model

In this case, the wave model of Fig. 3 is adopted. It allows generating a specific power reference. Figure 5 clearly shows the good power tracking performances and therefore confirms the effectiveness of the proposed model-based power predictive control strategy.

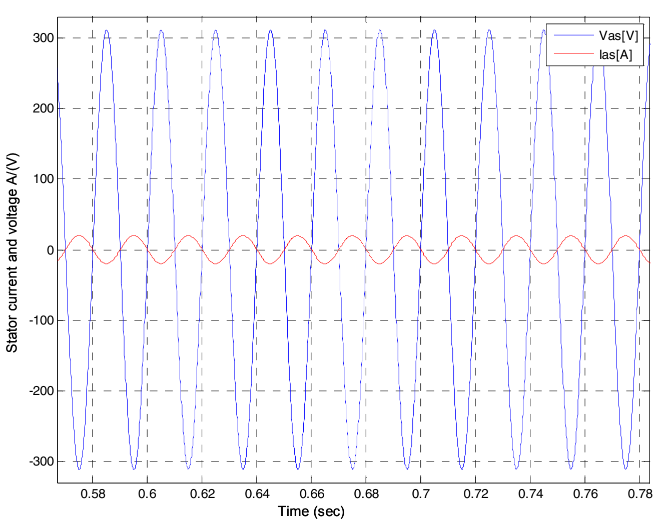
As in [11], extra simulation tests have been carried-out to further asses the effectiveness of the MBPC strategy.



(a) Active and reactive power responses.



(b) Capacitor voltage response.



(c) Rotor current and voltage responses.

Fig. 4. Step test reponses.

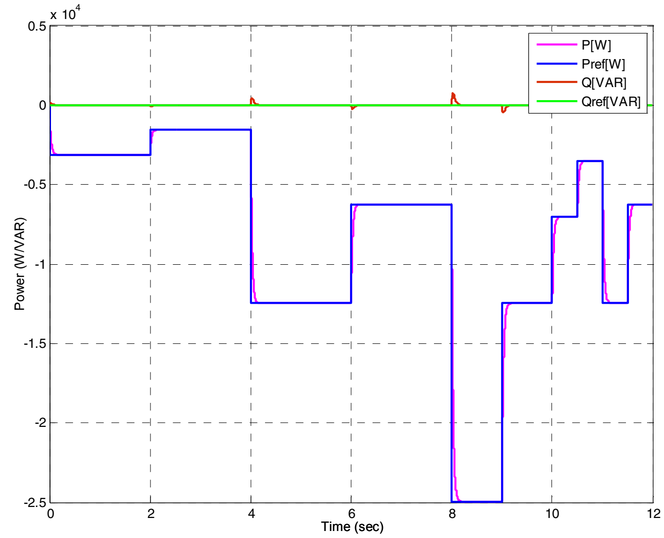


Fig. 5. Generated active and reactive powers.

In this context, various power steps are applied (i.e. from – 6 kW to – 15 kW).

As clearly shown in Fig. 6, good tracking performances are achieved in terms of DFIG active and reactive powers (Fig. 6a) as well as rotor currents (Fig. 6b).

VI. CONCLUSION

This paper dealt with a model-based predictive power control of a doubly-fed induction generator-based wave energy converter. In this context, the control law was derived from an objective function optimization (quadratic error between the predicted active/reactive powers and the specific references that are control-dependent. The predicted active/reactive powers were calculated using a linearized state-space model.

The obtained preliminary results clearly show the MBPC approach effectiveness in terms of DFIG active/reactive power tracking performances.

Further investigations are required to further asses the effectiveness of the proposed MBPC for different WECs [5].

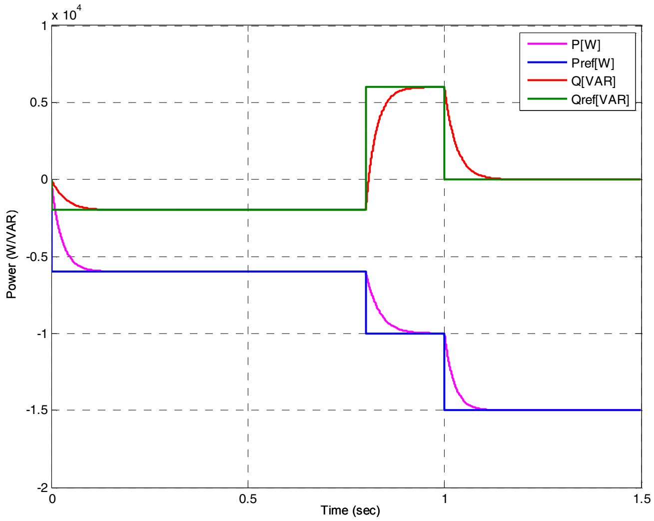
APPENDIX

RATED DATA OF THE SIMULATED DFIG

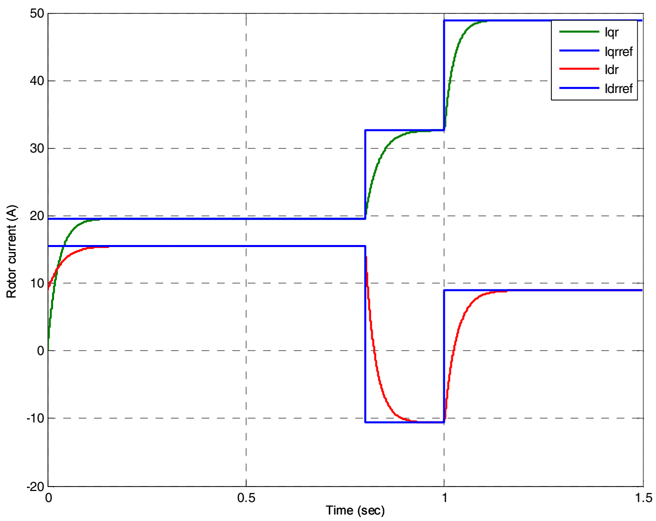
149.2 kW, $V_n = 575$ V, $p = 2$
$R_s = 0.002475\ \Omega$, $R_r = 0.0133\ \Omega$
$L_s = 0.000284$ H, $L_r = 0.000284$ H, $L_m = 0.01425$ H
$J = 2.60$ kg.m²

REFERENCES

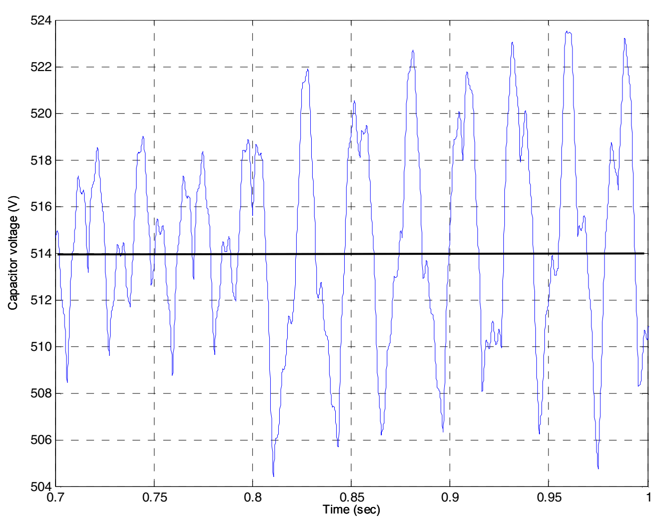
[1] J. Crus Ed., *Ocean Wave Energy: Current Status and Future Perspectives*. Springer, Berlin, 2008.



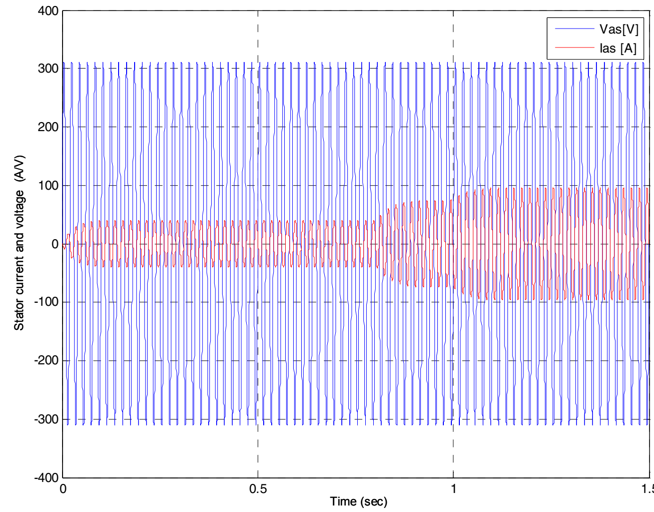
(a) Active and reactive power responses.



(b) *d-q* rotor current responses.



(c) Capacitor voltage response.



(d) Rotor current and voltage responses.

Fig. 6. Step test reponses with different operating speeds.

[2] J.G. Vining A. Muetze, "Economic factors and incentives for ocean wave energy conversion," *IEEE Trans. Industry Applications*, vol. 45, n°2, pp. 547-554, March-April 2009.

[3] S. Benelghali, M.E.H. Benbouzid and J.F. Charpentier, "Marine tidal current electric power generation technology: State of the art and current status," *in Proceedings of the 2007 IEEE IEMDC*, Antalya (Turkey), vol. 2, pp. 1407-1412, May 2007.

[4] http://www.emec.org.uk / (last accessed April 2012).

[5] M.S. Lagoun, A. Benalia and M.E.H. Benbouzid, "Ocean wave converters: State of the art and current status," *in Proceedings of the 2010 IEEE ENERGYCON*, Manama (Bahraïn), pp. 636-641, December 2010.

[6] B. Beltran, M.E.H. Benbouzid and T. Ahmed-Ali, "Second-order sliding mode control of a doubly fed induction generator driven wind turbine," *IEEE Trans. Energy Conversion*, vol. 27, n°2, pp. 261-269, June 2012.

[7] S. Benelghali, M.E.H. Benbouzid, J.F. Charpentier, T. Ahmed-Ali and I. Munteanu, "Experimental validation of a marine current turbine simulator: Application to a PMSG-based system second-order sliding mode control," *IEEE Trans. Industrial Electronics*, vol. 58, n°1, pp. 118-126, January 2011.

[8] R. Pena, R. Cardenas, J. Proboste, G. Asher and J. Clare, "Sensorless control of doubly-fed induction generators using a rotor-current-based MRAS observer," *IEEE Trans. Industrial Electronics*, vol. 55, n°1, pp. 330-339, January 2008.

[9] J.W. Park, K.W. Lee and H.J. Lee, "Wide speed operation of a doubly-fed induction generator for tidal current energy," *in Proceedings of the 2004 IEEE IECON*, Busan (South Korea), vol. 2, pp. 1333-1338, 2004.

[10] L. Xu and P. Cartwright, "Direct active and reactive power control of DFIG for wind energy generation," *IEEE Trans. Energy Conversion*, vol. 21, n°3, pp. 750-758, September 2006.

[11] A.J. Sguarezi Filho and E.R. Filho, "Model-based predictive control applied to the doubly-fed induction generator direct power control," *IEEE Trans. Sustainable Energy*, vol. 3, n°3, pp. 398-406, July 2012.

[12] A.J. Sguarezi Filho, M.E. de Oliveira Filho and E. Ruppert Filho, "A predictive power control for wind energy," *IEEE Trans. Sustainable Energy*, vol. 2, n°1, pp.97-105, January 2011.

[13] D. Zhi, L. Xu and B.W. Williams, "Model-based predictive direct power control of doubly fed induction generators," *IEEE Trans. Power Electronics*, vol. 25, n°2, pp. 341-351, February 2010.

[14] L. Xu, D. Zhi and B.W. Williams, "Model-based predictive direct power control of doubly fed induction generators," *IEEE Trans. Industrial Electronics*, vol. 56, n°10, pp. 4143-4153, October 2009.